REPORT ON THE APPLICATION OF DIGITAL COMPUTERS IN NUCLEAR POWER REACTORS

John A. Celmer

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The Pennsylvania State University

The Graduate School

Department of Nuclear Engineering

Report
on the Application of Digital Computers in Nuclear Power Reactors

A Paper in

Nuclear Engineering

by

John A. Celmer

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I. INTRODUCTION

With worldwide concern about the energy situation, many of the advanced industrial countries of the world are now planning for a rapid build-up in the share of electricity being generated by nuclear power. It is estimated that between 30 and 50 percent of the total electricity required by the end of the century will be generated by nuclear power.[1] The modern power reactors being designed and built to satisfy this demand for electricity are generally large and complex. For this reason the nuclear industry has now incorporated the use of a digital computer at many power stations throughout the world in an attempt to simplify the operation of the plant and thereby enhance the safety of the plant.

Generally, the computer is used to perform automatic system monitoring, plant performance calculations and rapid data recording. In this manner the computer functions in an advisory capacity to assist the reactor operator. In some countries the reactor operation has been simplified further by expanding the role of the computer to include the automatic control of the power plant and some of its auxiliary machinery. In Germany the computer is now planned to perform a role of major importance in the safety system of two reactors currently under construction.[2] Thus, the degree of automation at nuclear power stations has been increasing steadily during the last decade. What then is the status of the completely automatic reactor instrumentation and control system?

This paper will review the present status of various computer configured power reactors in existence and being developed in the world today. The major functions performed by the computer at each installation will be discussed and the unique features of each computer

configuration will be identified specifically. The major difficulties encountered and the degree of success of each configuration currently in operation will be pointed out. Finally a comparison of the automated functions of each reactor control system previously discussed will be made with general conclusions as to the future role of on-line computer systems in nuclear power stations.

II. BACKGROUND

The operation of power reactors requires that the operator monitor and record in-core temperatures, reactor power levels, reactor period data, control rod position indication data, auxiliary machinery status, coolant and steam flow rates and reactor pressures plus the status of various alarms and air monitors. Additionally the operator must make calculations for reactivity, xenon poisoning, rod calibration, flux mapping, power distribution and fuel management. In order to reduce the complexity and improve the safety of plant operations, on-line digital computers are now included as an integral component of most large nuclear power stations.[3]

The degree to which the computers are utilized in nuclear power stations may be functionally categorized as monitoring, control and protection applications.

Until recently, the primary purpose of on-line digital processing systems was that of a data collecting or monitoring nature, while control was left to the more conventional analog methods. The reluctance to permit participation of digital computers on a more active basis in the nuclear reactor control systems, particularly in the United States, was based mainly upon low reliability.[4] In the nuclear industry the safety requirements have been traditionally very stringent and a device with a low reliability could not be used for any essential purpose in the operation of the reactors. Therefore the reactors in some countries use the computer solely for monitoring purposes.

Power reactors are now being built and operated in Sweden, Pakistan, England, Canada and France; the designs, of which, include the

utilization of a process computer for the direct digital control of the reactor and other important plant variables. These reactor designs use aerospace reliability criteria and technology, including mathematical assessment of the mean time between failures (MTBF).[3] High reliability is achieved by the use of redundancy and testing. In these designs, the computer is an essential component of the control systems.

Conventional analog circuits with relay or solid-state logic circuits are used in the safety systems, which are sometimes identified as protection systems, of today's power reactors. The safety features afforded by the use of a computer at power stations today are generally limited to advising the operator of an alarm and the probable cause of the alarm. The newly designed Canadian reactors are an exception, however, since the computer is used to initiate a reactor trip condition as an added measure to augment the analog safety system.

A survey of the various types of power reactors which use digital computers has been conducted and a detailed description of the different computer schemes used to provide monitoring, control and protection functions is presented in sections III, IV, and V of this report. The power reactors built in other countries which are not mentioned in this report tend to be completely analog systems although extensive research in the area of digital control of reactors is being conducted in Switzerland, Belgium and Japan.[3,5,6]

III. MONITORING SYSTEMS

SEQUOYAH (UNITED STATES)

The Sequoyah nuclear power plant is one of the largest nuclear stations being built in the United States. It is being constructed by the Tennessee Valley Authority on the west shore of the Chickamouga Reservoir, approximately 18 miles northeast of Chattanooga, Tennessee. The plant will use twin pressurized water reactors which have been designed by the Westinghouse Electric Corporation. The reactors are rated at 3,423 MWt each and commercial operation is now scheduled for December 1974.[7] The plant will use the monitoring scheme depicted in Figure 3-1. Although the computer is an effective and valuable operational tool, the plant is designed on the basis that sustained, full power operation does not depend on the availability of the computer.

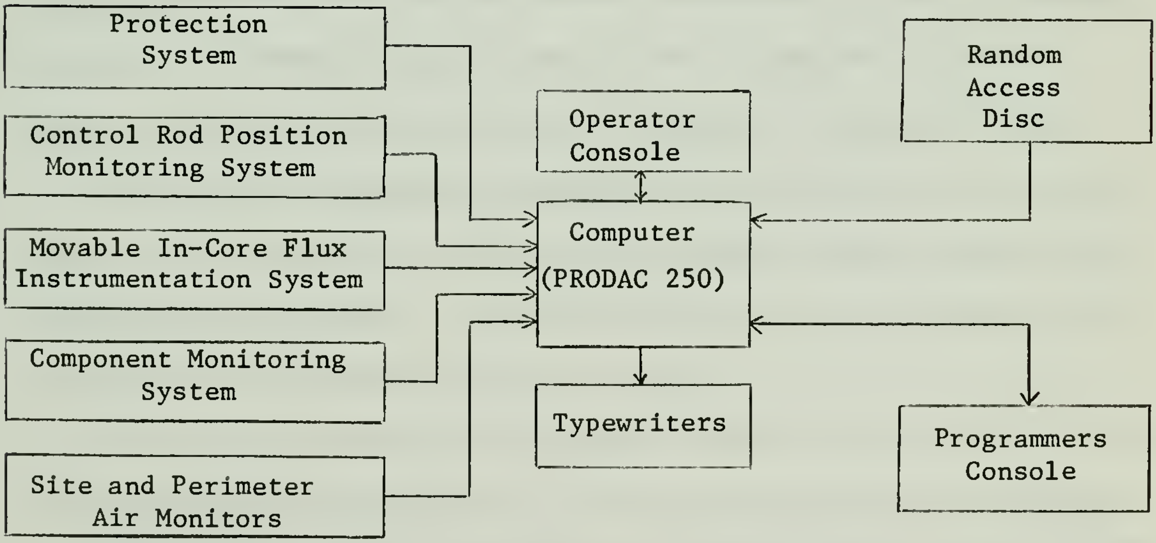


Figure 3-1

Simplified Block Diagram of Computer System

The protection system measures dominate nuclear plant process variables and provides continuous analog information to the operator. Additionally it provides approximately 20 reactor trip functions which stem from the measurements of primary system pressures, flows and levels, nuclear and thermal overpower, and secondary plant pressures, flows and levels. The bistable output of each channel of the protection system is coupled to the computer for data processing, printing and alarm indication.

The sensors from the control rod position monitoring system provide information to the computer which monitors deviations between rods in a group or bank, and actuates an alarm if the deviation exceeds pre-established limits.

The in-core instrumentation system provides information on the neutron flux distribution and the fuel assembly outlet temperature at selected locations within the core. This instrumentation system provides only for acquiring data and performs no operational control or safety function. Information thus obtained makes it possible to confirm reactor core design parameters and calculated hot channel factors.

The component monitoring system provides information to the computer on the operational status of various pumps, valves, motors and other reactor components. The data is stored and then printed on the log sheets at prescribed intervals of time.

The site and perimeter air monitors transmit data to the plant computer and the chart recorders for data recording and alarm indication.

The Sequoyah computer accomodates 975 analog input signals and 600 digital input signals. The working programs performed by the computer include analog and digital scanning, limit supervision and off-normal

condition alarms. Also included are protection system operation monitoring, flux distribution and hot channel factor calculations and secondary plant operational guidance and performance calculations.

Specific information regarding the programming technique used was not available to the author. However, it is envisioned that a time-sharing technique is utilized since this would enable the operator to use the on-line computer for diagnostic tests and general off-line applications.

This station is currently undergoing total system checkout and operational performance data on the monitoring system is not available.

CONNECTICUT YANKEE (UNITED STATES)

The Connecticut Yankee nuclear power station which was built by the Connecticut Yankee Power Company, is located in Haddam, Connecticut. The plant uses a pressurized water reactor which was provided by the Westinghouse Electric Corporation and is currently operating at 467 MWe. To maintain effective control and perform the constant measurements needed for efficient plant operation the station is equipped with a monitoring and information system based on an IBM 1800 data acquisition system with four on-line printers.[8] This power station is smaller than the Sequoyah plant and therefore less analog and digital inputs are required for the monitoring system. The simplified diagram shown in Figure 3-1 also applies for this station.

There are 317 analog inputs and 237 digital inputs to the computer. The analog inputs include signals from the protection system, 48 thermocouples that measure in-core temperatures, linear voltage differential transformers that measure control rod positions, amplifiers which are

connected to the in-core flux detectors, bearing thermocouples and many other sensors including site and air monitors. The digital inputs include 45 contact sense inputs to indicate the limiting positions of the control rods, contact sense inputs for in-core flux detection and path indications, several inputs to check auxiliary equipment operating conditions and status, and inputs from two console keyboards which enable digital interpretation of operator requests.

The digital outputs are used to actuate main control board annunciator panel lights which indicate specific computer originated alarms, to control two NIXIE tube displays and to actuate any of four printers.

A time-sharing executive programming technique is used in this system which generates a wide range of reports to be produced as the on-line data gathering function proceeds. The executive program, functioning as a programmed timer, controls the timing of various process analog scan programs. Typical of this type is the fast scan program which causes 132 analog points to be read. From this data, one minute averages and five minute averages are calculated. Typical of information monitored at this point are those inputs that permit the calculation of plant power output in thermal units based on a heat balance around the steam generators. Every 120 milliseconds, 108 digital inputs are scanned and brought into the memory. The data from each new input is compared with data from the previous scan. When there is a change a sequence of events message is printed to alert the main control board operator. This message indicates the time the reading was taken, the identification of the specific piece of equipment and the direction of the change, i.e., high or low, on or off, etc.

Other programs are maintained on a magnetic disk and are brought into the central processing unit by the executive program. These programs are used to provide trend reports, an alarm indication if a rod is not in step with the rod bank, post incident reports, limit supervision and plant performance calculations.

This computer system was valuable to the plant management during the critical checkout phases, and continues to be so.[8]

DOUGLAS POINT (UNITED STATES)

The Potomac Electric Power Company is currently planning to build a nuclear power station near Douglas Point, about 30 miles south of Washington, D.C. This station is to be distinguished from the power station in Canada which is also known as the Douglas Point nuclear power station.

The Potomac Electric Power Company is planning to use two boiling water reactors at the new station. The reactors are to be provided by the General Electric Company and each reactor is planned to produce 1,178 MWe. Construction of the facility is expected to begin in March of 1975 pending State and Federal approvals with completion of the first unit in 1980.[9] This plant will also use the basic monitoring scheme shown in Figure 3-1 but with noticeable improvements in the method of displays and the addition of a new computer function, turbine control.[10]

The latest state of the art technology will be used to reduce the number of display devices. Color cathode ray tube (CRT) displays will be employed to increase operator comprehension of the plant variables, improve operator response time and reduce operator fatigue. The color CRT displays (two per reactor unit) will display plant parameters in the

form of bar charts, graphics, digital readouts and alpha-numeric alarms. The displays will have a data switching network and in the event that one CRT fails the data can be shifted manually or automatically to a standby CRT display. These new consoles are also planned to be used at other stations which have boiling water reactors, such as the Berwick station which is being constructed in Pennsylvania.

The second improvement to the on-line processing system is the extension of the digital processing functions to include digital control of the turbine. This control function is a supplementary feature of the monitoring system. The automatic turbine supervisory and start-up mode of the digital electro-hydraulic control features permit the turbine start-up with a minimum number of operator actions. This system will enable the turbine generator to be rolled from turning gear to synchronous speed and locked into the grid automatically.

The computer system, one per reactor unit, will provide for scanning, performance calculations, logging and alarming of plant functions. In addition it will form the basis for gathering and manipulating plant information for the CRT display.

WYLFA (GREAT BRITAIN)

The Wylfa nuclear power station which became fully operational in 1969 employs two MAGNOX gas cooled reactors and was the first nuclear power station in Great Britain to make extensive use of the digital computer.[11,12] The previous application of the computer to power stations in Great Britain was at the Oldbury station where the computer was used for routine logging and alarm analysis.

The functions performed by the data processing system at the Wylfa plant include routine logging of plant variables, post incident analysis and logging, alarm analysis and display, limit supervision, plant performance calculations, core performance calculations and automatic turbine start-up. This computer system utilizes a CRT display to obtain centralized control of the plant operations.

Both of the reactors at the Wylfa station use the single computer system. This digital processing system is not indispensable since both units can run for several hours at constant load if the computer should fail. However, to increase the reliability of the station a standby computer with automatic switching features is provided, but this computer is normally used for off-line calculations. A schematic diagram of the computer configuration is provided in Figure 3-2. This configuration requires elaborate highway switching functions which must be programmed.

The computer system at the Wylfa station has been proven to be very reliable with availabilities exceeding the manufacturer's specified value of 99.8 percent as shown in Table 3-1.[12]

WÜRGASSEN (GERMANY)

The Würgassen nuclear power station uses a boiling water reactor. This power plant produces 640 MWe and full power operation was initiated in 1972.[13] Figure 3-3 shows the general outlay of the standard on-line computer system configuration which is used at this station as well as many other stations in Germany which use boiling water reactors.[14]

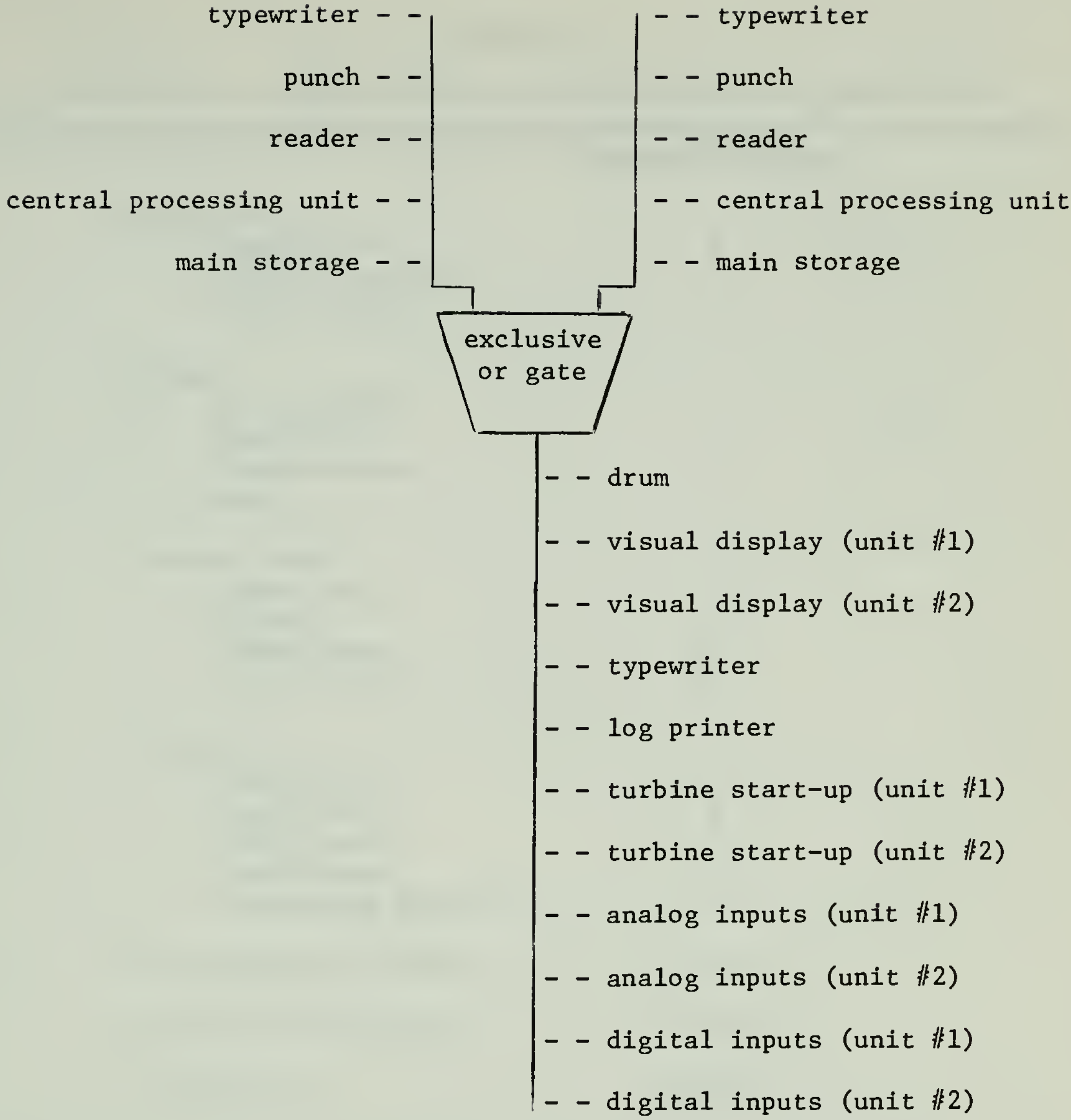


Figure 3-2

Wylfa Computer Configuration Schematic

Table 3-1

Reliability of Wylfa Computer System During a 52 Week Period

	number of faults
Processor:	
Transistors	2
Shorted Connector	1
Relay Contact	1
Drums:	
Maladjustment	1
Transistors	4
Potentiometers	1
Heads	3
Display Units:	
Transistors	5
Diodes	2
Vacuum Tubes	18
Capacitors	1
Scanners:	
Transistors	-
Capacitors	2
Transformers	1
Reed Relays	48
Interposing Relays	1
Total number of faults	93
Total system down time	3.1 hours
Availability	99.96%

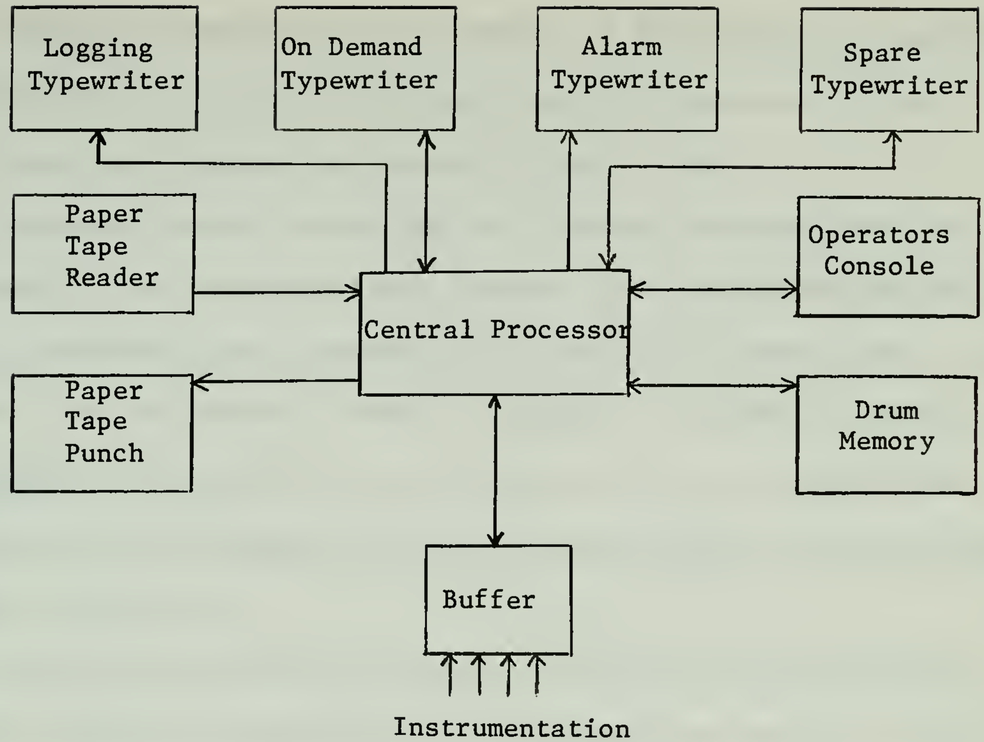


Figure 3-3

Wurgassen Computer System Configuration

The computer system uses an AEG 6050 computer which is comparable to the GE/PAC 4020 computer having core memory of 32,000 words. The drum memory size is 256,000 words. The processor accomodates approximately 1,000 analog inputs and 1,000 digital inputs. With this extensive number of inputs available, primarily from the in-core instrumentation, it is very important that a sufficient number of values be read at a high speed. The analog inputs are categorized into 4 scan classes, with a scanning every 5, 15, or 60 seconds. The scan rate of the digital inputs is 883,000 bits/second.

The master computer program consists of three blocks of individual programs which are used for core performance calculations, plant performance calculations and administration of data.

Core performance calculations are the most important functions performed by the computer in this design. The computer determines the three dimensional power distribution together with thermal limit calculations. In this manner a better knowledge of the power distribution is obtained which enables the operating limits on the critical heat flux ratio and the maximum heat flux to come closer to the real thermal limits of the fuel.

The computer determines the power distribution from ionization chamber readings, thermo-hydraulic measurements and control rod positions using expansion techniques to cover the unmonitored region between detectors.

In addition to this key task, various other calculations are performed. Some examples are:

(1) Calibration of in-core chambers,

(2) Control rod position indication,

(3) Determination of variable limits,

(4) Determination of exposure distribution,

(5) Determination of fuel isotopics,

(6) Determination of control blade and in-core chamber exposure, and

(7) Xenon poisoning predictions.

The computer also performs plant performance calculations which determine steam flow, plant efficiency, electrical power and condenser state.

The administrative program generates trend logging, alarm indication, routine logging and post incident analysis.

In this reactor design, the basic monitoring functions have been expanded. The computer is programmed as an open loop controller so that the operator is automatically advised of the adjustments that are necessary to maintain the plant operation at peak efficiency.

OBRIGHEIM (GERMANY)

The use of the computer as an open loop controller has also been incorporated in the design of many pressurized water reactors in Germany, such as at the Obrigheim nuclear power station which currently produces 300 MWe. The computer system has been in operation with the reactor loaded since July 1968.[15] It has essentially the same computer configuration as previously described for the Würgassen station, Figure 3-3, except that a Siemens 300 data processing system is used.

The distinguishing feature of this design is the extensive operational information that is provided automatically to the operator. Summaries of the supervisory functions, logging functions, core performance calculations and plant performance calculations that are performed automatically are provided in Tables 3-2, 3-3, 3-4, and 3-5.

The design approach for the new reactors being built in Germany is based upon the open loop controller principles just described. Currently it is not planned to expand the role of the computer to that of a closed loop controller in the future German reactor designs.[16] This decision results from cost and performance considerations.

Table 3-2

Supervisory Functions Employed in Obrigheim Nuclear Power Station

Reactor coolant system
- monitoring of reactor coolant pump shaft seals

Steam generators
- tube plate temperature protection
- tube failure check
- heat-up gradient
- activity leakage from blowdown lines

Pressurizer
- start-up and shutdown pressure gradients

Volume control system
- volume control tank H_2O pressure monitoring
- reactor coolant purification rate inlet control

Turbine
- barring gear operation on shutdown

Component cooling loop
- activity check
- regulation of spent fuel pit cooling water temperature

Ventilation systems
- monitoring of air handling in primary shield cooling system
- monitoring of exhaust air filter operation
- monitoring of reactor building and annular space air pressure
- quick-closing damper checking
- monitoring trend of pressure and temperature in reactor building
- monitoring of spray system in reactor building

Purification system
- monitoring of anion exchanger regeneration

Condensate pumps
- pump wear

Feed heating system
- tube failure checks
- air removal checks

Feed water tank
- deaeration checks
- pressure drop checks in the event of a reactor trip

Feed pumps
- impeller wear
- balancing system wear
- minimum and maximum flow checks
- emergency feed pump minimum pressure checks

Table 3-3

Logging Functions

Employed in Obrigheim Nuclear Power Station

- fault log
- post incident review
- switching log
- operators action log
- analog trend log
- operating daily and monthly logs
- operating time log
- maintenance work log
- integrated value log

Table 3-4

Core Performance Calculations

Employed in Obrigheim Nuclear Power Station

In-core instrumentation evaluation and power calculations	Thermal and reactivity calculations
- corrections for in-core instrumentation	- thermal power
- resolution errors of scintillation counters	- hot channel factors
- ball stack residual activity	- minimum DNB ratios
- decay rate at end of activation	- xenon predictions
- temperature effect	- use of control rods and chemical shim
- power distribution	- reactivity balance
- power density peaks during load changes	
- axial burn-up distribution per fuel assembly	

Table 3-5

Plant Performance Calculations

Employed in Obrigheim Nuclear Power Station

Water/steam cycle in turbo-generator	Reactor plant and auxiliary systems
- heat rate deviation	- control rod monitoring
- condenser performance	- functional monitoring of neutron flux instrumentation in the counting and intermediate ranges
- generator loading	- flow rate determination of reactor coolant loops
- generator H_2 losses	- reactor vessel heat build-up monitoring
- demineralized water quality and flow checks	- liquid effluent decay tank storage capacity
- demineralized water consumption	- monitoring and balancing of gaseous and liquid activity discharges (overall values and specific nuclides)

IV. CONTROL SYSTEMS

MARVIKEN (SWEDEN)

The Marviken prototype power plant which has been built in Sweden to produce 200 MWe uses a boiling heavy water reactor with internal superheating.[17] This is a single cycle system with reactor steam going directly into the turbine.

Since the Marviken station was the first full-scale prototype of this kind to be built the required degree of automation for the plant operation was investigated in detail. Manual control with conventional relay logic was compared with on-line computer control. It was found that an on-line computer control would give the best flexibility especially when altering the condition of the plant cycle from saturated steam to superheated steam.

There are 32 superheater channels spread out over the reactor core. The throttle valves in the channels must be set in positions which give the same output temperature in all channels. If for any reason the temperature goes up in one channel, not only the valve in this channel but also the valves in the surrounding channels must be adjusted. The control sequence is difficult to accomplish manually and for that reason a direct digital control scheme was employed.

A block diagram of the computer configuration is shown in Figure 4-1.

The main functions of the computer are:

(1) Indication of process variables such as temperature or pressure,

(2) Printing of process variables and operations,

(3) Alarm annunciation and alarm analysis,

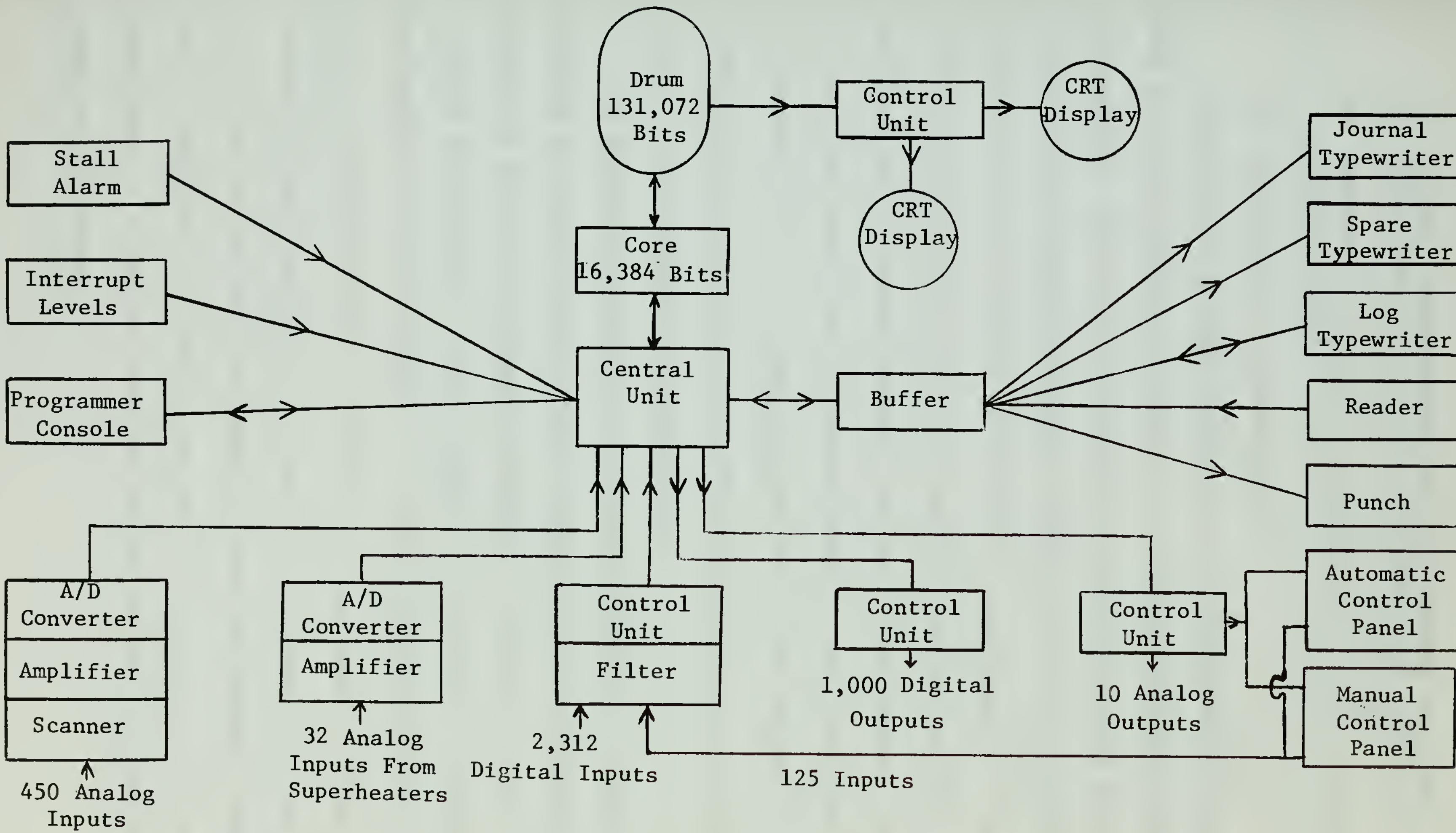


Figure 4-1

Marviken Computer Block Diagram

(4) Automatic sequence control for starting up, normal running, refuelling and testing of machinery and valves,

(5) Automatic setting of the throttle valves in the superheater channels, and

(6) Calculation of channel power.

Indication of process variables such as temperature or pressure is made on the CRT displays instead of on several hundreds of indicating instruments. Every process variable or analog input has its own identification code consisting of three figures, one letter and three figures. The alpha-numeric identification code appears on the CRT followed by the measured value of the selected process variable. These variables may be printed whenever desired by the operator. Additionally, every two hours the 200 process variables being monitored are printed automatically on the logging typewriter in the computer room. Alarms are also indicated on the CRT display and alarm messages are printed on the typewriter automatically.

The automatic operation of the station requires 46 sequence control programs and some of these control programs require intermittent manual operations before the automatic sequence is completed. After being advised of the need for a manual operation the operator initiates a program which causes the computer to check the parameters which are important for the next sequence of events. If the measured values exceed the previously specified limits the operator is advised of an error condition which must be corrected manually before the automatic sequencing can be continued. For every operation in the automatic sequence programs there is a list of conditions which must be fulfilled before the operation is performed.

Table 4-1

Number of Programs Required

for Automatic Sequence Control

Start-up	8 programs
Normal running	1 program
Shutdown	6 programs
Refuelling	17 programs
Tesing of machinery and valves	14 programs

The number of sequence programs required for the various automatic modes of operation are shown in Table 4-1.

The channel power is calculated by means of the in-core flux monitoring system which uses beta current detectors.

The computer system just described is an integral part of the reactor design and must therefore function properly when the reactor is being operated. Since redundancy is not employed in the computer system, a failure in this system will cause the reactor to be inoperable.

This station was closed down in 1970 and an assessment of the performance of the digital control system could not be ascertained.

KANUPP (PAKISTAN)

The Kanupp nuclear power station uses a pressure-tube, heavy water moderated, natural uranium reactor which was designed and built for the Pakistan Atomic Energy Commission by the Nuclear Energy Project of Canadian General Electric.[18] This power plant became operational in December 1972 and produces 137 MWe.[19]

A pair of digital station control computers, having identical hardware characteristics, provide the following functions:[18]

(1) Dual channel, direct digital control of reactor power,

(2) Automatic turbine load control,

(3) Flux tilt control,

(4) Fuel channel outlet temperature monitoring,

(5) Failed fuel activity monitoring,

(6) Alarm annunication,

(7) Thermal power calculation,

(8) Xenon poison calculation and prediction, and

(9) Station logging.

The neutron flux level of the reactor is controlled to match the turbine demand and to maintain a nominally constant steam pressure to the turbine during power generation.

There are two modes of plant operation; frequency control and base load operation. When operating in the frequency control mode the turbine increases or decreases its power output during frequency deviations to help maintain the grid at its desired frequency of 50 Hz. During base load operation the plant load controller, also a computer function, acts to maintain the electrical power output at the desired value by manipulating the setpoint of the mechanically actuated turbine governor. The plant power output still responds to frequency deviations but only momentarily as the plant load controller corrects all lengthy deviations from the desired power output.

The reactivity control systems can be divided into two groups based upon operating speed. The fast acting systems include (1) moderator level control which is the primary method of reactivity control and

(2) control of the booster and absorber rod movement. The slow acting systems consist of continuous on-power refuelling and moderator poison (boron) concentration adjustments. The fast acting systems are controlled by the computers.

Fine control of reactivity is effected by adjustment of moderator level. Each computer regulates its own moderator level control valve. The two control valves are installed in parallel to ensure that the channel demanding the lower power will always be in control, the other channel acting as a backup. Rod movement to increase reactivity requires the agreement of both computers. Either computer acting alone can move the rods to decrease reactivity.

The controller can best be described by considering it to consist of two control loops in cascade and a third independent loop.

The primary or outer loop, shown in Figure 4-2, combines measurements of steam flow and steam pressure into a neutron flux level setpoint for the secondary or inner loop.

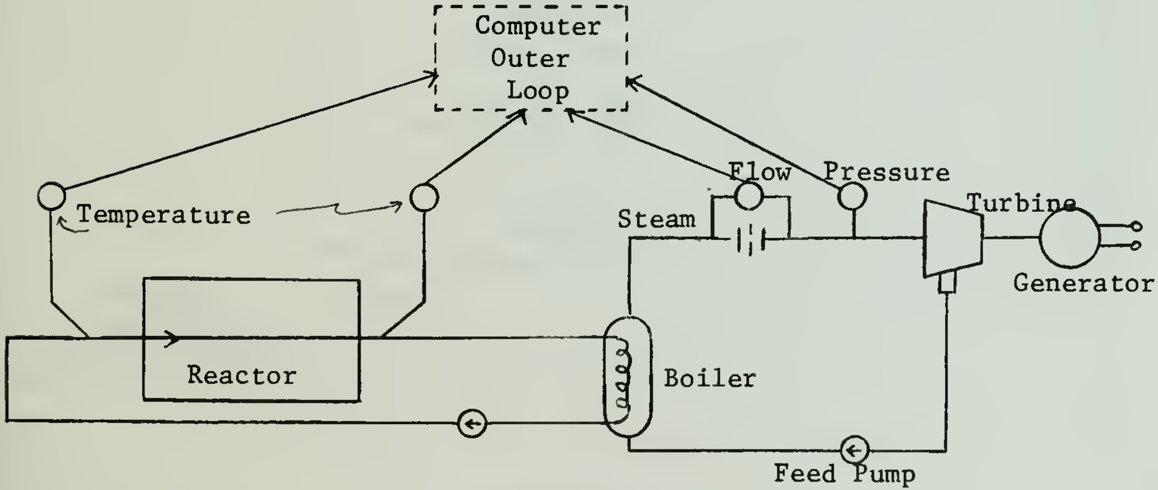


Figure 4-2

Schematic of Kanupp Outer Loop

The inner loop, shown in Figure 4-3, adjusts reactivity by manipulating the moderator level control valve to maintain the neutron flux level at the value demanded by the outer loop. The variables monitored by the inner loop are linear neutron flux (LIN N), log neutron flux (LOG N), rate of change of log neutron flux (RATE LOG N) and moderator level (H) all of which are employed in the control equations.

A third loop monitors the moderator level and adjusts reactivity using the control rods to force the inner loop to maintain the moderator level in the control region at the top of the calandria.

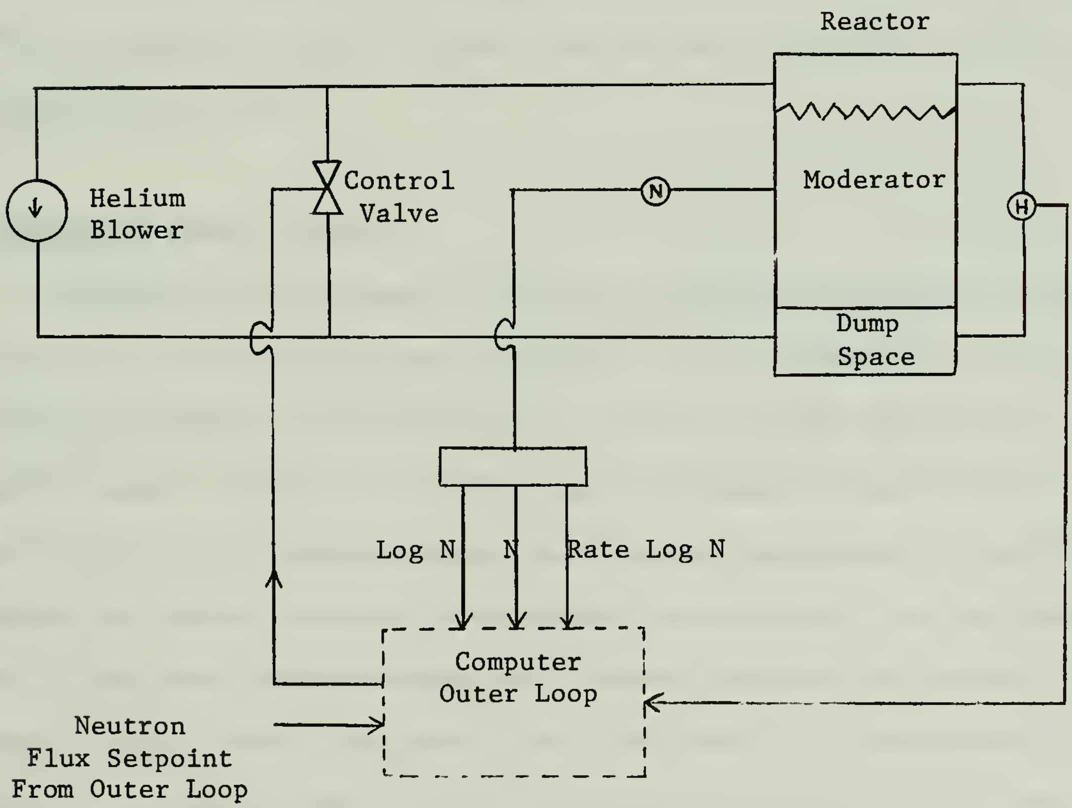


Figure 4-3

Schematic of Kanupp Inner Loop

The control equations were developed using an analog computer programmed to simulate the reactor, boiler and turbine. These equations were optimized to provide stable control under all plausible conditions, taking advantage of the capabilities of the digital computer which make practical the inclusion of non-linear compensation.

The open loop cross-over frequencies of the control loops were then determined and a bandpass filtering circuit was devised which would eliminate disturbances from noise. The filtering circuit was designed so that the total phase lag introduced by sampling and filtering at the open-loop cross-over frequency of the system was limited to 8 degrees.

The completed power plant is now operating satisfactorily at rated power although the control program required some modification during commissioning in 1972.[19]

DUNGENESS B (GREAT BRITAIN)

The United Kingdom Central Electricity Generating Board has computers in all of its nuclear power stations.[12] The Dungeness B station, which is currently being commissioned, uses two 660 MWe advanced gas-cooled reactors (AGR) each of which has an independent computer system.[11,12,20] The computer system is a logical development of the Wylfa system but greater reliance is placed upon the computer. The reliability of the basic computer system was therefore improved by providing a common standby central processing unit (CPU) which could automatically replace the defective CPU of either reactor-turbine unit. The standby CPU would normally be available for off-line calculations. The block diagram is shown in Figure 4-4.

The data processing functions performed at the Wylfa station are

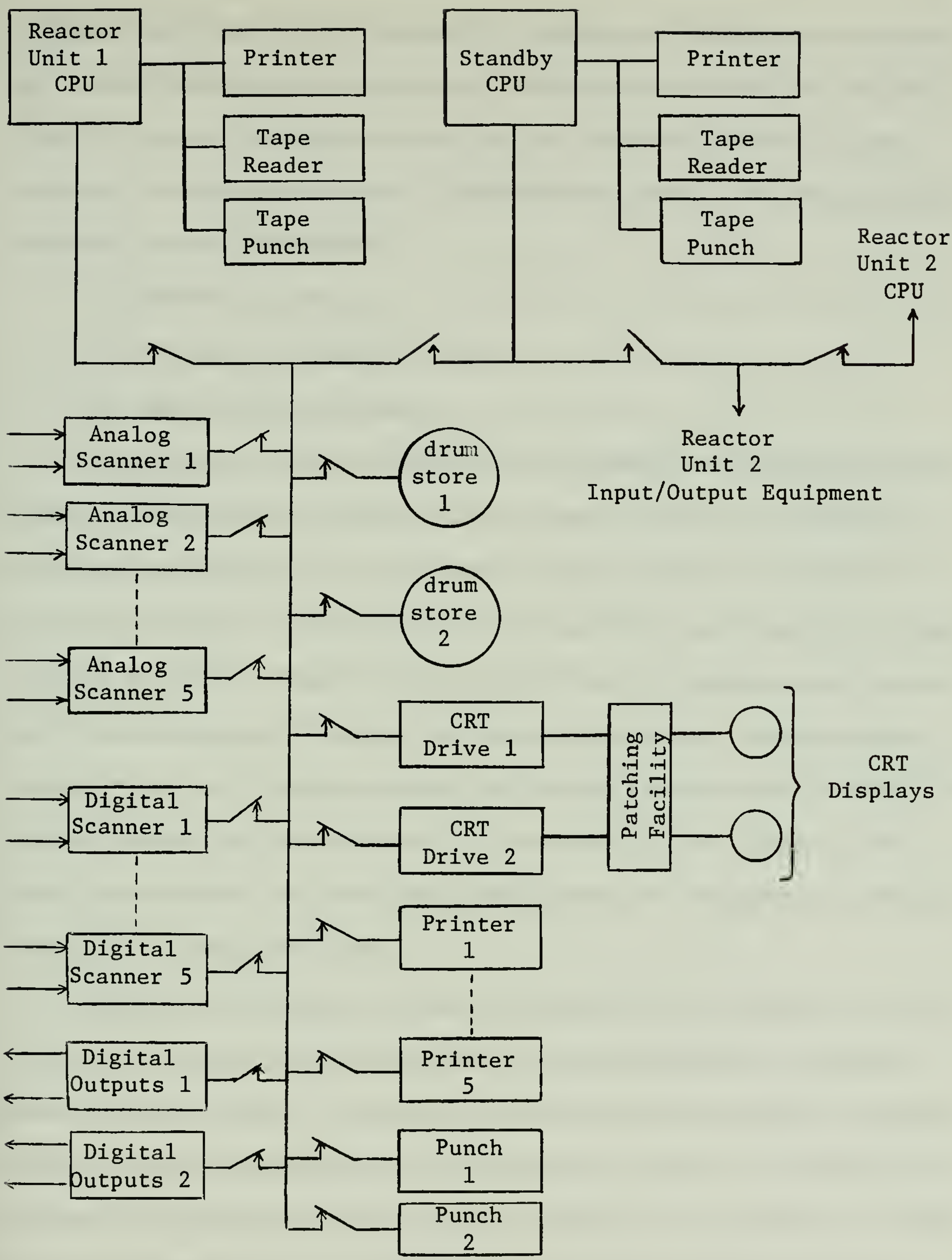


Figure 4-4

Block Diagram of Dungeness B Computer System

likewise performed at the Dungeness B station and additional processing and control functions are provided. The facilities which are in addition to those of the Wylfa station are an increased degree of alarm analysis, a comprehensive fault identification system and the following automatic control functions:

(1) Reactor start-up,

(2) Reactor zone control, and

(3) Reactor flux scanning.

The purpose of alarm analysis is to condense the information presented to the operator to that which he needs to know for immediate action while filtering out extraneous signals which are incidental to the action required. The results of the analysis are displayed in plain language on a CRT. Signals derived both from the digital alarm inputs and from analog input scanning routines are logically combined where necessary in the processing system with plant state signals derived from further digital and analog inputs to give valid alarm signals. The valid alarm signals are displayed immediately upon detection on the unit operator's alarm display CRT.

A fault identification routine is then initiated whereby the valid alarm signals are processed according to the requirements of stored alarm causation trees. The output from the causation analysis identifies one or more alarm signals as a prime cause alarm for any particular pattern of alarm inputs. This data is provided to the operator by means of the CRT display and is automatically printed on the log printer.

The automatic control of the reactor during start-up is initiated by the operator after he manually energizes the circulator motors and completely withdraws the trim and zone rods.

The data processing system then initiates the withdrawal of the rod banks while monitoring three pulse channel power levels and period signals. The withdrawal of the rod banks is stopped if an abnormality occurs. In this case manual intervention is required to initiate the program after correction of the abnormality.

As criticality is approached the start-up program is discontinued and the rod banks are adjusted to bring the reactor to the desired reactor period. When the reactor period has been stablized in the required range, further rod bank movement is stopped and the neutron density continues to diverge at the established rate until the predetermined flux level is reached.

When the required level of neutron flux has been reached, and the rate of rise of the coolant outlet temperature is sufficient to demand an initial downward movement of the zone rods, the zone control program is initiated and the movement of the zone rods is automatically started by the reactor zone controller. This continues until the zone controller has increased the reactor channel gas outlet temperature at a predetermined rate up to the initial desired level.

The zone control program and reactor start-up program maintain the reactor in a stable condition by continuous control of the zone rod position and intermittent movement of the rod banks until the rod banks are fully withdrawn or the operator selects the manual mode of operation.

A large reactor tends to require control against spatial instabilities and in this case the reactor is divided into five zones each of which is controlled by an individual control rod. The control rod is

part of a servo loop which keeps the average channel gas outlet temperature constant in each zone for a given power level. Thus zone control is a part of the overall station control system and the desired value of the reactor gas outlet temperature can be made to vary in such a manner as to control the boiler outlet steam temperature. The zone gas outlet and steam temperatures are controlled by cascaded digital controllers.

For core performance calculations and for estimates of maximum fuel element temperature, it is necessary to know the axial flux shape. This is measured in the reactor by pneumatically transporting miniature ball bearings into nine totally enclosed vertical steel tubes at different radial positions in each reactor core. Each column of balls corresponding to the height of the reactor core is irradiated for a predetermined period. The balls are then pneumatically transferred from the reactor for measurement of power distribution by an annular ion chamber and amplifier. The balls are retained in the ion chamber for subsequent storage. Axial in-core flux shapes are determined using this equipment which is controlled automatically by the reactor flux scanning program.

The data processing system at the Dungeness B station is currently operational and is being used for the testing and checkout of the station during commissioning. The station is expected to be operational in 1975.

Numerous software difficulties have been encountered in this installation resulting in extensive cost increases. The programming effort in preparing the software for the Dungeness B computer system amounted to 30 man-years.[16]

HINKLEY B (GREAT BRITAIN)

The Hinkley B nuclear power station in Great Britain is currently being commissioned and is expected to be in operation by December 1974.[11,12] This power plant also uses dual advanced gas-cooled reactors.

The functions provided by the computer system at the Hinkley B station are very similar to those at the Dungeness B station but in this case the computer system is more sophisticated. Basically the computer configuration used in the Dungeness B station specified the use of a single highway for each reactor unit, whereas the Hinkley B plant has two highways for each reactor unit and each highway can be automatically switched to either the unit computer or the standby computer. Additionally, the number of inputs and outputs interfacing with the processing system differ at each station. The Hinkley B plant is expected to operate in the manner previously described for the Dungeness B station.

HARTLEPOOL (GREAT BRITAIN)

The newest computer configuration to be used at a nuclear power station in Great Britain is currently being manufactured for the Hartlepool station which is planned to be fully operational in 1976.[11,12,21,22] This station will employ twin advanced gas-cooled reactors each of which will produce 660 MWe.

This station will rely upon on-line data processing systems to provide data displays, logs and extensive direct digital control. A new concept which was introduced in the design of this system is that

the scanning equipment is local to the plant areas which reduces the amount of cabling that would otherwise be required.

The data processing system provides facilities for two reactor, boiler, turbine and generator units. Associated with each unit is one computer and a block of input and output equipment. This provides 2,560 analog inputs, 2,350 contact inputs, 384 relay outputs, 7 CRT display units and various teleprinters, paper tape punches and tape readers. The third computer acts as a standby to either of the main units. When the standby computer is not on-line, it is used for maintenance purposes. A schematic of the computer configuration is provided in Figure 4-5.

The computer configuration permits the independent switching of any of the 4 blocks of input and output devices between the unit CPU and the standby CPU. Each unit computer is programmed with an automatic switching program known as the watchdog timer which provides automatic central control of the highway block switching function. By using these switching techniques a very low overall system failure rate is anticipated. A failure rate leading to a reactor shutdown is predicted to be less frequent than once in 20 years.

The reactor and plant performance entails complex interacting control requirements and the control loops are non-linear. In this system the computer controls:

(1) Reactor gas outlet temperature, by varying the position of any of 37 rods,

(2) Reactor gas inlet temperature from 8 boiler units, by varying gas flow,

(3) Boiler feedwater flows, by altering turbine drive or electrically driven feed pumps,

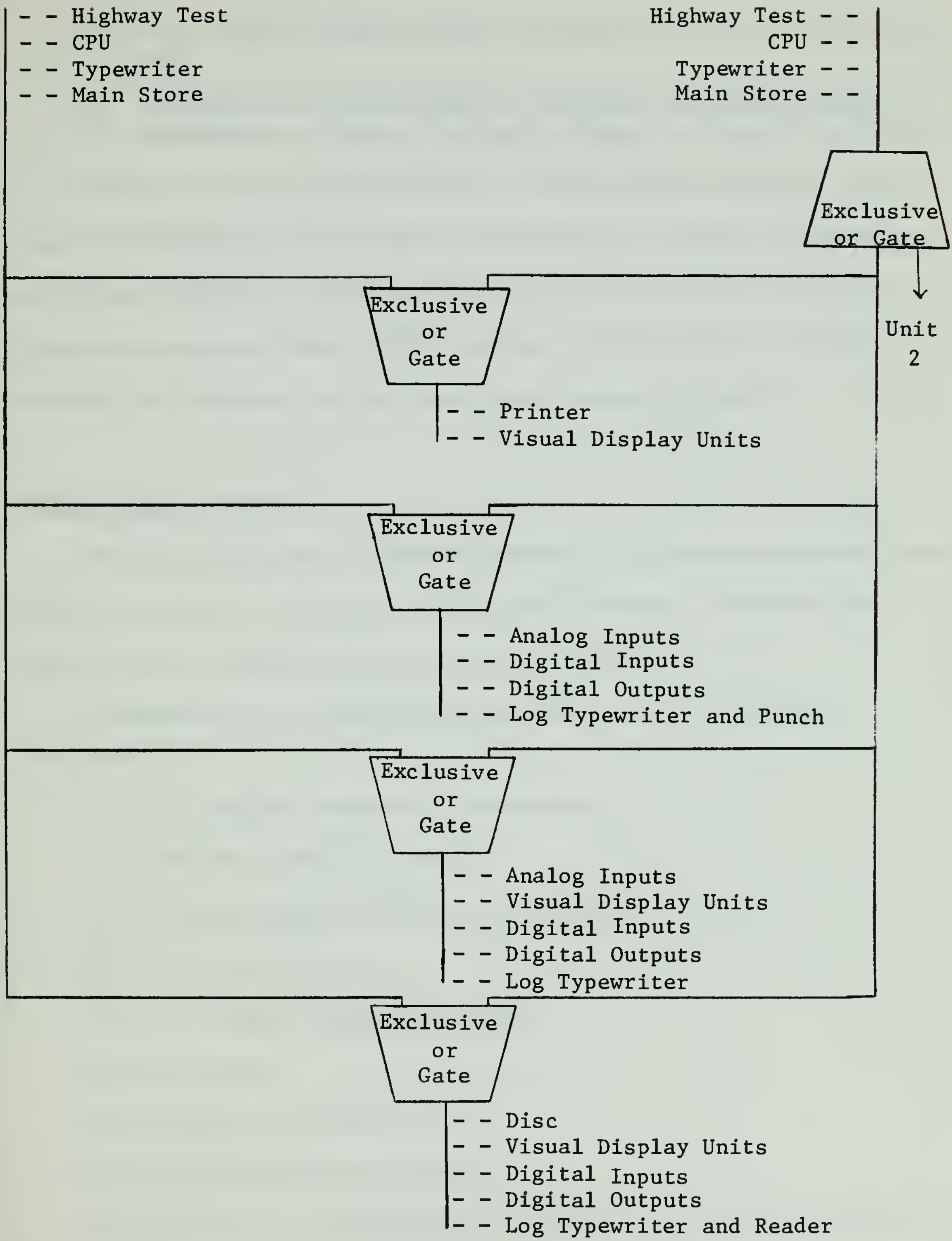


Figure 4-5

Hartlepool Computer Configuration Schematic

(4) Main turbine steam pressure by varying the throttle valves, and

(5) Integration of those control functions providing frequency compensation, reactor rod bank trimming and load scheduling.

Station start-up is controlled by the computer in phases, covering rod withdrawal to criticality, automatic flux control, initiation of boiling followed by turbine driven feed pump run-up and takeover from electric pumps, main turbine run-up, synchronization and block loading, and transfer to full power under automatic control.

DOUGLAS POINT (CANADA)

The first step toward computer control in a Canadian nuclear power plant was taken at the Douglas Point power station, a 200 MWe unit which employs a pressure-tube heavy water reactor.[23,24,25]

At Douglas Point a single computer performs the following functions:

(1) Fuel channel temperature monitoring,

(2) Reactor flux-tilt control,

(3) Alarm scanning, checking and logging,

(4) Station hourly log,

(5) Fuel channel temperature log,

(6) Trend log,

(7) Display of variables, and

(8) Xenon poisoning monitoring.

The computer was introduced into the system as shown in Figure 4-6. Two major control loops are indicated. An analog system is used for fast power regulation, whereby a combination of ion chamber and thermal signals control the reactivity by means of moderator level

adjustment. A direct digital control loop is used to counteract any flux tilt. It adjusts the position of mechanical absorbers in response to temperature sensors that provide a measurement of radial power distribution. Additionally, a minor control loop permits the computer to adjust the power level demand. The computer is programmed to take into account the electrical output required by the power distribution system and any power limiting factors imposed by the station itself.

Another important feature is the connection to the reactor safety system. In this design the computer may be used to shutdown the reactor if a dangerous condition exists. This circuitry is in addition to the independent safety system which is described in section V.

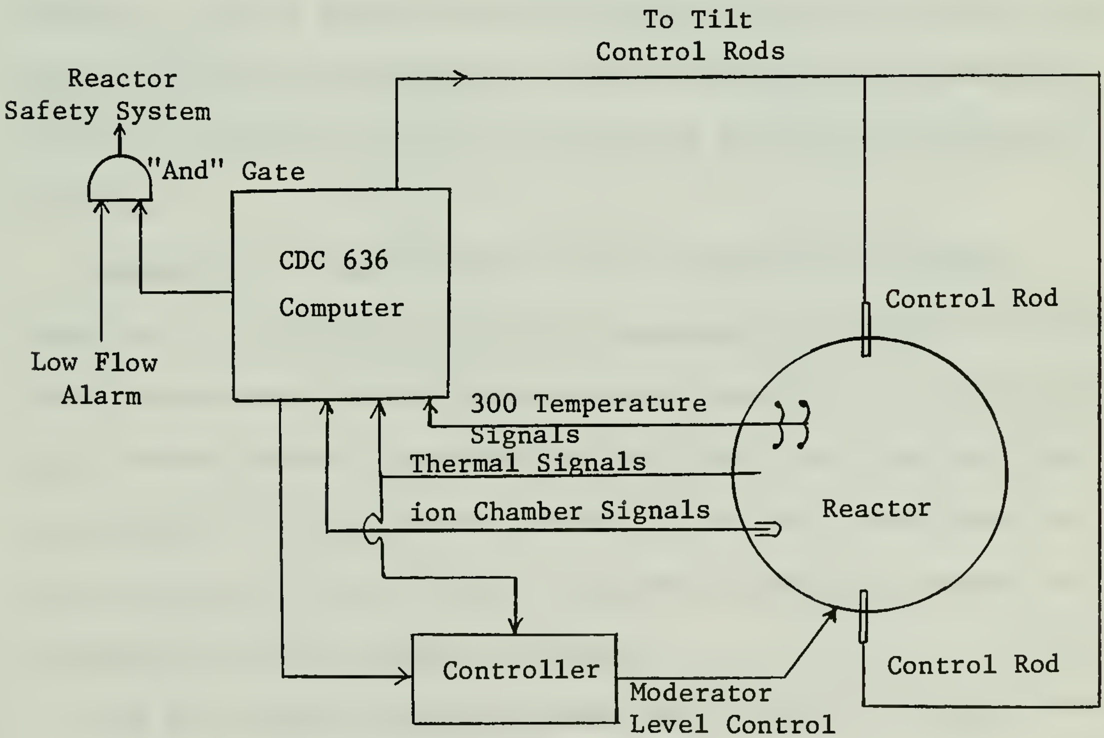


Figure 4-6

Douglas Point Computer Control System

Failure of the computer in the Douglas Point system does not force a reactor shutdown and manual operation is possible but at the expense of a greater work load for the operating staff.

The performance of the computer system at this station has been reliable with system availabilities greater than 99.92 percent.

PICKERING (CANADA)

The Pickering station was the next nuclear power station built in Canada which is heavily committed to computer-based control and instrumentation systems.[23,24,25,26] The station has four pressure-tube reactors which use natural uranium fuel with a heavy water moderator and coolant. Each unit is capable of producing a net power output of 500 MWe. Three of these units are producing their rated power at the present time and the fourth unit is being started. Each generating unit has two fuelling machines for changing fuel while operating at full power.

Reliability of the Pickering control system is of paramount importance both for cost and safety considerations. To meet this reliability requirement, a dual computer system design was selected which would provide complete redundancy at each unit. All functions that are essential to the operation of the unit are fully duplicated in both computers. The dual computer systems are identical except for the number of process inputs and outputs.

The dual computer approach chosen was to have one computer operating as the normal control system with the other taking on the role of an operating standby. Both computers have their inputs connected all of the time and both function as though they are controlling but only

the normal system has its outputs connected to the controlling element. A block diagram of one half of the computer system is shown in Figure 4-7.

The reactor regulating system shown in Figure 4-8 determines the power produced from two different sets of flux measurements. Ion chambers are used below 15 percent of full power and in-core flux detectors are used above 15 percent of full power. The programs have direct digital control over 14 light water compartment absorbers, 18 adjuster rods, 11 shutoff rods and 4 moderator level control valves.

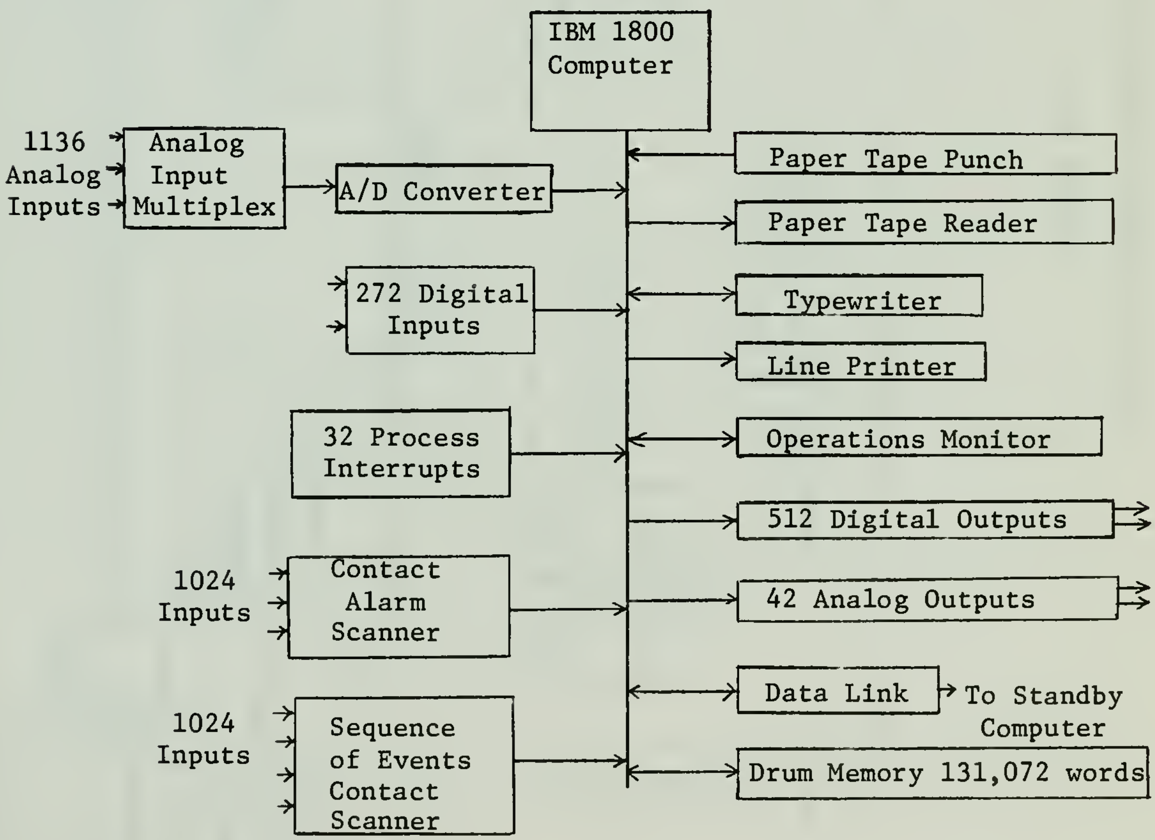


Figure 4-7

Pickering Computer Configuration Schematic

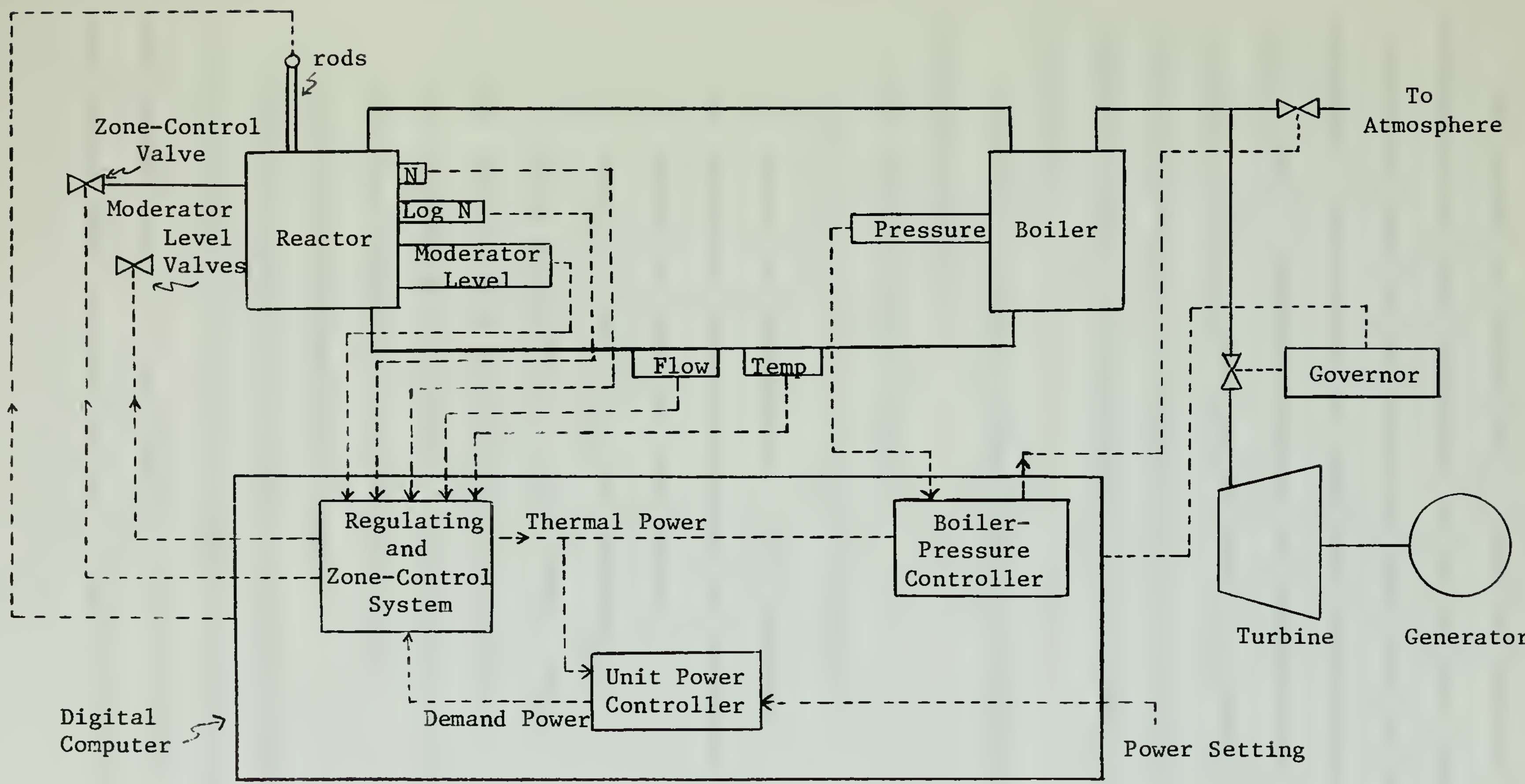


Figure 4-8

Pickering Computer Control System

The reactor is divided into 14 zones to counteract the spatial variation due to xenon poisoning. In the middle of each zone there is a compartment that can be filled with light water and by the automatic adjustment of the valve on the light water inlet the level in the compartment can be controlled and hence the neutron absorption can be controlled. These absorbers are actuated independently in response to in-core flux detectors that measure local perturbations or they are actuated in unison as a bulk reactivity control when a power alteration is required.

In addition to reactor power control the computer performs the following functions:

(1) Boiler pressure control,

(2) Control of reactor warm-up and cooldown,

(3) Control of loading rate of the turbine,

(4) Control of the turbine run-up and preliminary checks,

(5) Control of generator power output,

(6) Control of refuelling and sequencing,

(7) Alarm annunciation in main control room,

(8) Monitoring of fuel channel temperature,

(9) Continuous calculation of xenon poison concentration,

(10) Data logging and trend recording, and

(11) Plant performance calculations.

At the Pickering station there was complete operator acceptance of the computers and the functions necessary for plant operation since the plant cannot operate for any length of time without them. The executive program which provides the main timing for the system was subject

to a large number of refinements. One of the main problems was that the three timers used for timing control were all connected to the same interrupt level and could not be separated. Thus it took certain combinations of functions to occur in certain sequences to cause a fault. This problem has subsequently been corrected.

Some programming difficulty has also been observed with the CRT alarm display. The alarm messages were too abundant, lengthy and difficult to read. Consequently the alarm analysis and display programs were modified to increase the usefulness of the CRT display.

There have been three cases in which a unit has been shutdown due to a computer system failure. In the first case a hardware fault induced by lack of air conditioning caused the master computer to halt and transfer control to the standby computer. During the process a relay failed to close (presumably for the same temperature problem). The second outage was caused by a combination of hardware and software faults. The third outage occurred when a failed digital output relay caused a turbine run-back to be initiated and the power was decreased to 2 percent. In each case the problems were identified quickly and the plant was restored to operating power levels before the xenon concentration became inhibitive.

The computer systems have provided successful and flexible direct control. They have considerably reduced the commissioning times of the three Pickering units and met the requirements for reliable power production.[24]

GENTILLY (CANADA)

The Gentilly power station started producing its rated power, 250 MWe, in May 1972.[27] The reactor uses natural uranium fuel with a heavy water moderator and is cooled by boiling light water.

As in the Pickering station, the computer system for the Gentilly reactor exercises direct digital control of many vital functions as indicated in Figure 4-9.[23,27,28] The dual computer approach discussed previously is used at this station to assure that the computer system has a high reliability.

The coarse adjustment of reactivity for large power alterations is achieved by direct computer control of 16 booster rods. Six coolant flow valves are also controlled as a function of power.

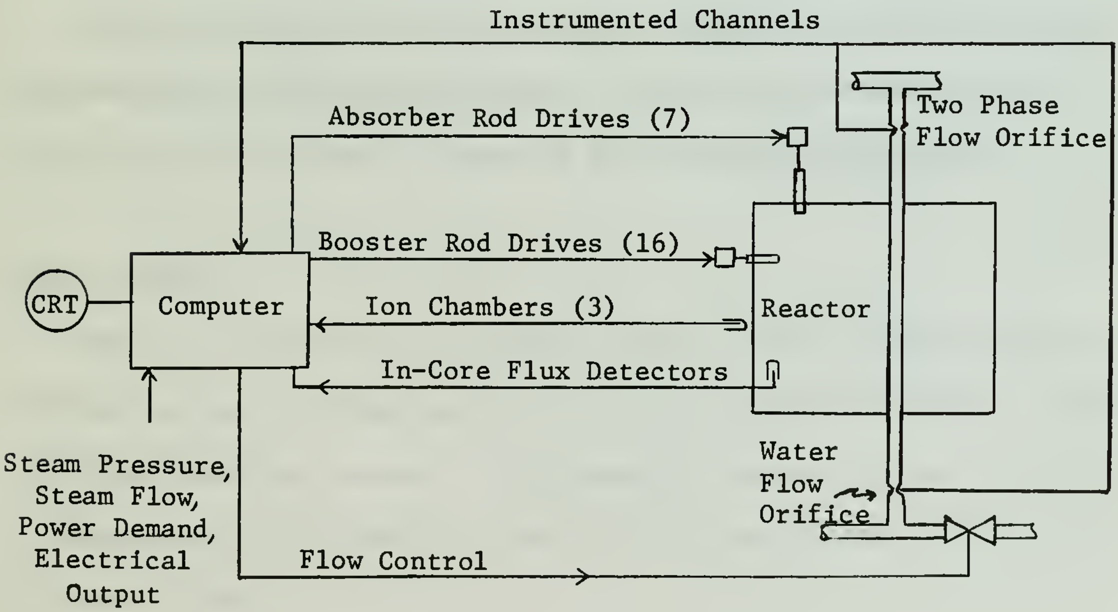
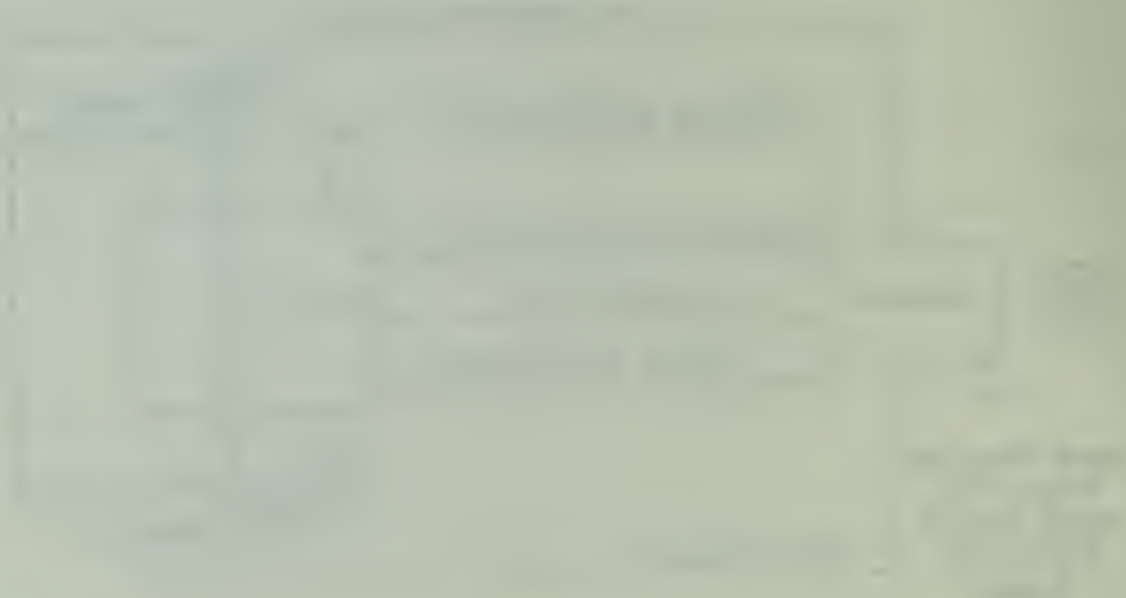


Figure 4-9

Gentilly Computer Control System



Continuous regulation of reactor power is done by the automatic adjustment of seven absorber rods which are driven in and out of the reactor by means of digital stepping motors. The seven absorber rods are distributed among seven zones in the reactor core to maintain spatial control of the reactor. The rods move together, for bulk control, in response to a combination of ion chamber and thermal signals but can be moved independently to achieve spatial control.

Signals for spatial control are obtained from forty fuel channels that are instrumented with inlet and outlet flow measuring orifices. Steam quality and hence channel power is derived from these measurements.

A CRT display is incorporated into the system. The display provides time-amplitude traces, bar graphs, absorber and booster rod positions, alpha-numeric messages and power distribution plots.

Flux tilt control difficulties were encountered during commissioning and after modifying the computer programs and installing a flux tilt protective system the computer system functioned properly.

<u>BRUCE</u> (CANADA)

Bruce is a four unit generating station with a nominal rating of 800 MWe per unit.[25] Each unit has a pressure-tube reactor with a heavy water moderator and coolant. The scheduled in-service dates are unit 2, September 1, 1976; unit 1, June 1, 1977; unit 3, June 1, 1978; unit 4, June 1, 1979.

A schematic of one half of the computer system is shown in Figure 4-10. The design approach for this computer system was essentially the approach used at the Pickering station, both with regard to the

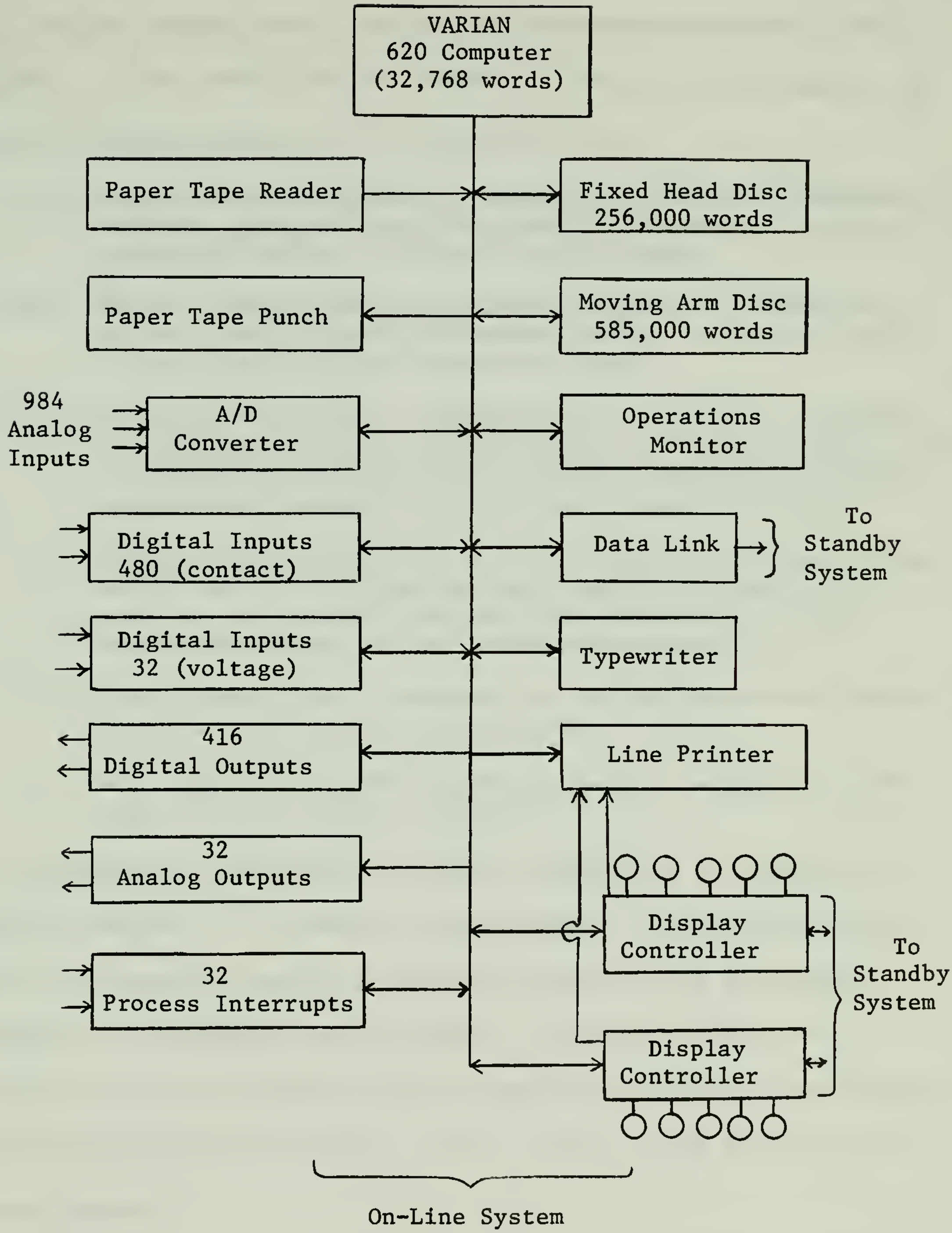


Figure 4-10

Bruce Computer Configuration Schematic

dual computer concept and to the process functions performed by the computer. In the broad areas of control, alarm, and data logging, the computer system performs the following functions:

(1) Reactor power regulation, implemented by means of a number of programs, each dedicated to a specific regulating task as the regulating needs of the plant might dictate,

(2) Boiler pressure control, attained normally by varying the reactor power setpoint, but occasionally, as the need arises, by operating the steam discharge valves,

(3) Unit power regulation, consisting of two distinct functions: to regulate the rate of plant warm-up and boiler pressure, and to adjust the setpoint of the reactor power regulating sub-system which controls the electrical output of the unit,

(4) Turbine run-up, consisting of an extensive set of preliminary checks and of a program that will run-up the turbine to speed in the shortest possible time consistent with the restraints imposed by the turbine manufacturer,

(5) Alarm annunciation, consisting of the monitoring and analysis of all major alarms on the unit, and

(6) Data logging, designed to produce periodic station and unit logs, as well as trend reports.

As mentioned previously, the design approach of the processing system is similar to the design approach used at the Pickering station. The truly innovative aspect of the Bruce system is its man-machine subsystem. Improvements were necessary in this area due to the increased size and complexity of the plant which dictates more frequent interaction between the operator and the plant control and instrumentation system.

The computer-driven CRT display system being designed for each unit of the generating station consists of ten CRT monitors driven by two controllers, eight keyboards and two high speed printers. The processing system can control up to eight monitors each of which has a vertical raster similar to a television receiver. The characters are

normally generated from dot matrices. The alpha-numeric and graphic characters can be individually added or deleted.

All analog inputs connected to either of the two unit control computers can have their values displayed on any CRT monitor except the alarm annunciation monitor. A group of related inputs can be displayed together for visual analysis and correlation.

SAINT LAURENT (FRANCE)

Digital computers are also used at the Saint Laurent nuclear power station to control the setpoints of an analog controller which, in turn, adjusts the reactivity of the plant.[28] This system also uses redundancy to obtain the necessary reliability. Additional details concerning the control of the plant are not available to the author.

V. SAFETY SYSTEMS

All of the modern nuclear power stations in service today use a safety system which is independent of any computer application although there is a definite trend to include a process computer in the safety systems in some of the new nuclear power stations being built in Germany.[30]

The conventional safety systems utilize relay logic or solid-state logic to trip the reactor. A block diagram of a typical modern safety system is shown in Figure 5-1.[7]

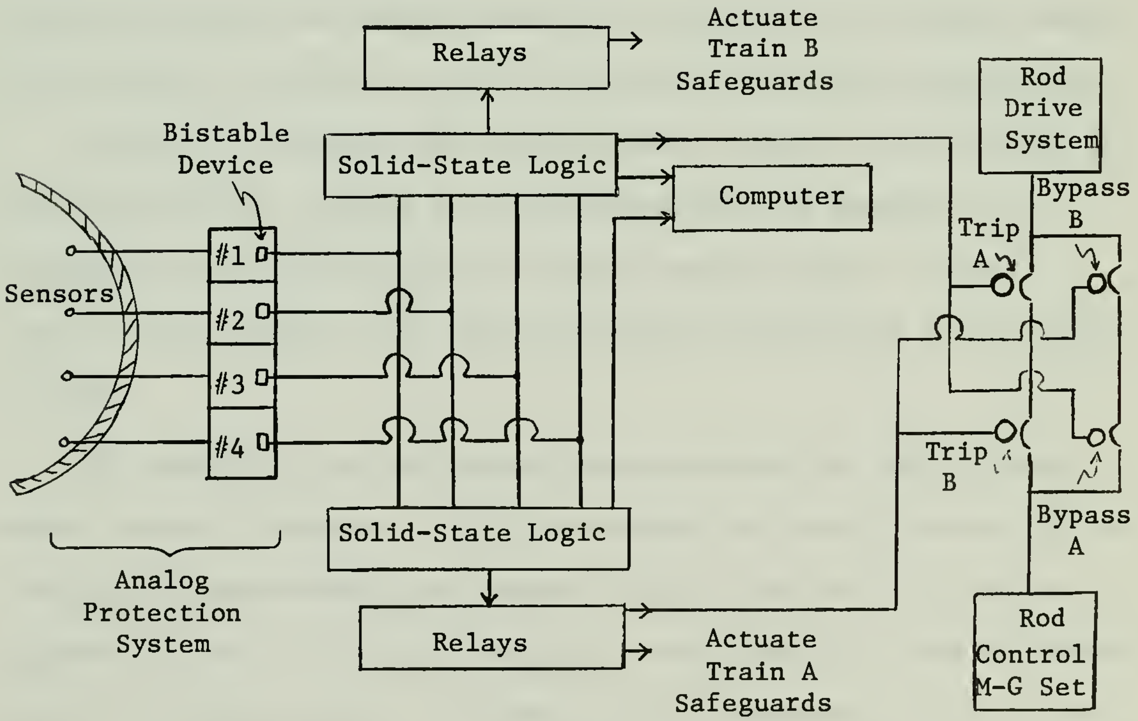


Figure 5-1

Blcok Diagram of Channelized Safety System

(Sequoyah Nuclear Power Station)

In this design the instrumentation system measures dominant nuclear plant process variables which include primary system pressures, flows and levels, nuclear and thermal power, and secondary plant pressures, flows and levels. The final device in the analog channel is a bistable device which serves as the input to the logic channels. As shown in Figure 5-1, the reactor is tripped when the electrical power to the control rod drive mechanism is interrupted by either of two series connected trip breakers. Two logic trains (A and B) are provided. Each train is associated with one of the trip breakers. The logic train accepts on or off signals from the bistable device, performs the required logic and actuates its associated trip breaker. In the event of a dangerous operating state the reactor is automatically tripped. The only function the computer serves with regard to the safety system is to monitor the status of the alarms and provide alarm annunciation.

The use of computers has been extended, however, in the design of two nuclear power stations which are being built in Germany, the Brunsbüttel and the Philippsburg nuclear power stations.[2] These stations have boiling water reactors and are scheduled to be in service in 1975.

The design of this new safety system requires the use of three single purpose computers. All of the analog and binary signals (48 and 168 signals respectively) are scanned with a cycle time of 30 milliseconds in each of the three computers. After analog to digital conversion, the analog signals are tested for non-transgression of a tolerance band and limit values. All transgressions are stored, as are also all non-permissible combinations of binary signals. These entries are evaluated by another program and, depending upon the circumstances,

result in a reactor trip which is triggered directly by the computer after an increase in the length of the computer pulses from 80 micro-seconds to 50 milliseconds. This safety system is currently being evaluated on the Halden reactor in Norway.[30]

VI. CONCLUSIONS

A summary of the computer monitoring and control functions for each of the nuclear power stations previously discussed is provided in Tables 6-1 and 6-2 respectively. The functions which are automatically performed at each station are indicated by an asterisk (*) and those functions which are not applicable for the type of reactor being considered are indicated by a dash (-).

Tables 6-1 and 6-2 show a definite trend toward a high degree of automation in the control of nuclear power stations. Completely automatic control systems are now in existence. Although the software development for the automated systems is a costly, tumultuous task it has been shown at several automated power stations now in operation that the performance of the computer monitoring and control systems has greatly simplified the plant operations and therefore improved the safety of the power plant.[8,12,18,24]

France, Great Britain and Canada are now heavily committed to the use of direct digital control systems for their reactors, and extensive research involving digital control systems is being conducted in the United States, Belgium, Switzerland and Japan.[3,5,6,30]

The special purpose computer is now planned to be used in the safety system of two German reactors because of its flexibility in analyzing the analog data and its self-checking features.

In the United States new multiplexing designs for power reactors are being evaluated.[31] A distinguishing feature of these designs is the ability to incorporate changes which would enable the use of a computer for digital control at some future date.

The liquid metal fast breeder reactor currently being developed in the United States will use approximately 1,000 in-core monitoring devices to assure the safety and the availability of the plant.[32,33,34] The handling of the data from these sensors seems feasible only by a computer, in which case, the control requirements would be carefully reviewed to determine the amount of automation that is necessary. Thus it is possible that the breeder reactor would have a significant degree of automation.

In view of the recent strides in automation of nuclear power plants coupled with the improvements to be gained in the areas of plant efficiency and safety it is envisioned that the United States will eventually develop a fully automatic nuclear power station.

Table 6-1

Summary of Computer Monitoring Functions

	OBRIGHEIM (GERMANY)	CONNECTICUT YANKEE (US)	WYLFA (ENGLAND)	WÜRGASSEN (GERMANY)	SEQUOYAH (US)	DOUGLAS POINT (US)
IN-SERVICE DATE	1968	1968	1969	1972	1974	1980
Routine Logging and Trend Reports	*	*	*	*	*	*
Post Incident Logging and Analysis	*	*	*	*	*	*
CRT Data Display			*			*
Alarm Display	*	*	*	*	*	*
Alarm Analysis	*	*	*	*	*	*
Limit Supervision	*	*	*	*	*	*
Plant Performance Calculations	*	*	*	*	*	*
Core Performance Calculations	*	*	*	*	*	*
Turbine Start-up Control			*			*

Table 6-2

Summary of Control Functions

	MARVIKEN (SWEDEN)	DOUGLAS POINT (CANADA)	PICKERING (CANADA)	KANUPP (PAKISTAN)	GENTILLY (CANADA)	HINKLEY (ENGLAND)	DUNGENESS B (ENGLAND)	HARTLEPOOL (ENGLAND)	BRUCE (CANADA)
IN-SERVICE DATE	closed	1967	1971	1972	1972	1974	1975	1976	1976
Routine Logging and Trend Reports	*	*	*	*	*	*	*	*	*
Post Incident Logging and Analysis	*	*	*	*	*	*	*	*	*
CRT Display	*		*	*	*	*	*	*	*
Alarm Display	*	*	*	*	*	*	*	*	*
Alarm Analysis	*	*	*	*	*	*	*	*	*
Limit Supervision	*	*	*	*	*	*	*	*	*
Plant Performance Calculations	*	*	*	*	*	*	*	*	*
Core Performance Calculations	*	*	*	*	*	*	*	*	*
Turbine Start-up Control			*	*		*	*	*	*
Control of Loading Rate of Turbine			*	*		*	*	*	*
Reactor Start-up Control	*		*	*	*	*	*	*	*
Reactor Coolant Outlet Temp. Control	*	–	–	–	–	*	*	*	–
Reactor Coolant Inlet Temp. Control		–	–	–	–			*	–
Reactor Coolant Mass Flow Control			*	*	*			*	*
Feed Flow Control			–	*					–
Refuelling Control			*						*
Flux Tilt Control		*	–		*			–	–
Zone Control			*		*	*	*	*	*
Plant Power Setpoint Control		*	*	*	*	*	*	*	*
Reactor Flux Scanning Control		–	–	–	–	*	*	*	–
Boiler Pressure Control			*						*

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